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Gasoline Additives Solve Injector Deposit Problems

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ABSTRACT

Once largely limited to relatively expensive low-production high-performance cars because of higher cost than carburetion, fuel injection has become increasingly used on cars throughout the world. In the U.S., the primary driving force has been easier control of exhaust emissions and improved fuel economy. However, deposits formed in the delivery area of the injector can reduce fuel economy and increase emissions. Tests have shown that some gasoline additives can clean up injectors and keep them clean. These additives also improve carburetor cleanliness.

BACKGROUND

Gasoline fuel injection has been used by the world automotive industry for many years. Prior to the mid-1970's, fuel injection systems were primarily limited to relatively expensive high-performance European cars, primarily because of their higher cost ($450 to $800 versus $150 for carburetors). Fuel economy was not the top engineering priority and the multiport system was used at that time for good drivability and performance.

Today, however, multiport fuel injection systems are becoming common on current design automobiles. It has been estimated that about 85% of cars produced in 1990 will be equipped with multiport fuel injection. (1)*

The main advantages of fuel injection are:

1. Excellent startability under all conditions.
2. Good drivability (i.e., no tip-in problems or surging).
3. Less tendency to knock.
4. Ability to control emissions when used with electronic control systems.
5. Improved fuel economy.

In the U.S., the primary driving force for equipping vehicles with fuel injection has been easier control of exhaust emissions (fuel-air ratio) and improved fuel economy. Although fuel injection systems have a high first cost, they are normally considered to be extremely trouble free. Customer acceptability is high, primarily because drivability is greatly improved over that of carbureted cars.

FUEL INJECTION PROBLEM

Multipoint fuel injectors are precision pieces of equipment. A typical injector is

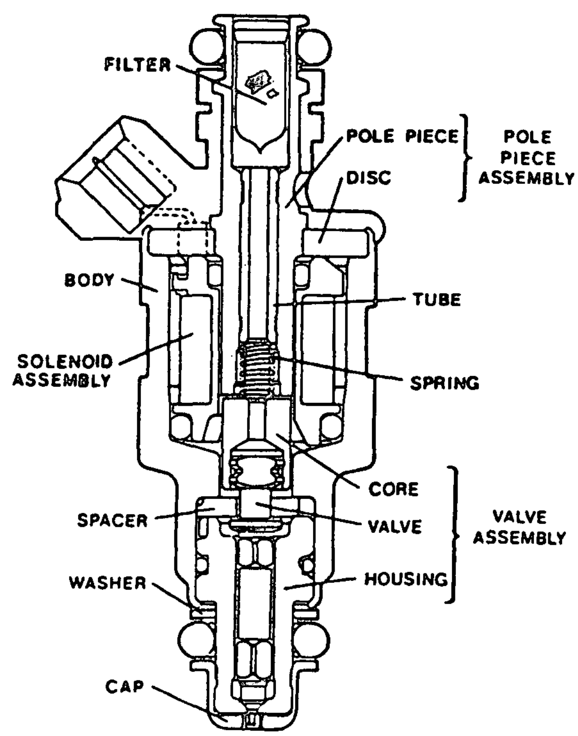

Figure 1. Typical Port Injector

*Numbers in parentheses denote references at end of paper.

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shown in Figure 1. This unit is basically a solenoid valve whose open-close frequency can be varied by an electronic control system. A major problem is occurring with these injectors. During operation, a small amount of deposit forms in the pintle fuel delivery area. This deposit, which can be varnish or coke-like in appearance, reduces the fuel flow to the cylinder. When flow is reduced by about 20%, driver complaints begin to occur. The car is hard to start and has tip-in and acceleration problems. This can occur in less than 1000 miles with some model cars.

Many investigators believe that several variables are involved. These are:
1. Fuel composition
2. Engine design
3. Driving-soak cycle

The problem was first reported at high altitude in Chrysler Turbo cars. However, it is now occurring in fuel-injected cars throughout the U.S. and with most gasolines. The seriousness of the problem can be judged from the fact that both CRC and SAE have formed groups to study this problem.

ETHYL'S APPROACH TO STUDYING FUEL SYSTEM CLEANLINESS

When studying fuel system cleanliness, there are two areas of potential interest -- clean-up and "keep-clean".(2)(3) Clean-up is usually the most difficult of the two areas. When it is achieved, keep-clean follows easily. However, concern had been expressed by some investigators that studies of gasoline fuel injector clean-up would require a dirty-up procedure followed by clean-up testing. We wanted to determine if dirty injectors from the field could be used for clean-up studies. However, these injectors must not show clean-up merely by re-running them with Indolene test fuel. In other words, clean-up should not occur when using a non-additive base fuel. We checked this concept by testing a fouled set of injectors on Indolene alone. Table 1 demonstrates that this concept was correct. Previously fouled injectors can be used for clean-up studies since no clean-up occurs on the base fuel alone after 250 miles.

Table 1

Injector Flow Rates
Using Non-Additive Indolene

Injector No.	Injector Flow Rate*, g/min. 0 Miles	250 Miles
1	203	202
2	130	130
3	208	208
4	75	90

*Flow specification for a new Chrysler injector is 208 g/min. ± 3%.

A second concern we had about this method was based on extensive prior work with diesel fuel injectors.(4)(5) Removing diesel injectors for flow test in a pressure rig environment frequently resulted in altering the injector deposits during the flow test. Obviously, this would preclude further meaningful mileage accumulation. As emissions are a reflection of fuel quality, metering, and spray, we decided to employ both routes until we were satisfied that the flow test measurement (Table 1) had no deposit removal effects. We were confident that deposits would not be altered since gasoline fuel injection pressures are at least an order of magnitude below diesel fuel injection pressures.

In the final analysis, both routes (emissions and flow checks) were found acceptable and had other respective uses in moving this program forward.

INJECTOR DEPOSIT ANALYSIS

The industry first became aware of the injector problem when Chrysler began to discuss it at the CRC automotive committee meetings. After several discussions with Chrysler, we were able to obtain samples of fouled injectors. Analysis showed that the deposits were primarily carbon, with sulfur being the largest inorganic fraction.

SPECTROSCOPIC EXAMINATION OF A FOULED INJECTOR - Two injectors were dismantled and analyzed by reflectance Fourier-Transform spectroscopy. The infrared beam was focused onto the pintle tip and shaft by means of a glazing angle infrared microscope. A representative spectrum is shown in Figure 2.

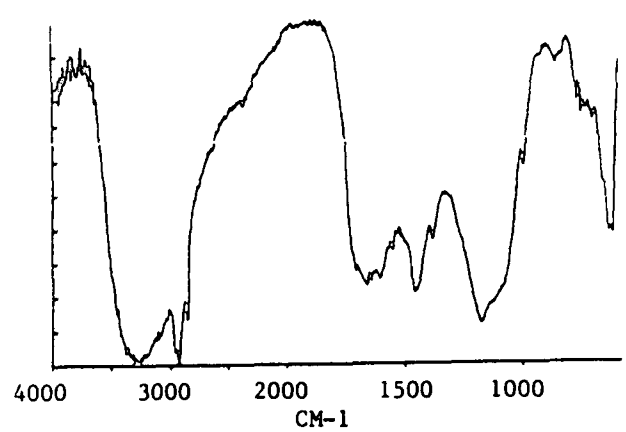

Figure 2. FTIR of Injector Tip Deposit

The spectrum of the injector deposit is somewhat similar to a typical spectrum of varnish from the oxidized oil, as from a Panel Coker. Although it cannot be claimed that lubricating oil was the cause of injector deposits, oxidation was involved.

Also, there were significant differences between the two spectra. The injector spectrum showed the presence of oxidized hydrocarbons (3000-3500 cm^{-1} and 1600-1500 cm^{-1} and unsaturates (1700-1600 cm^{-1}). The oxidized hydrocarbons are not the typical components observed from excessively oxidized motor oils, such as ketones and esters. Instead, the oxidized hydrocarbons were carboxylic acids and salts.

The most interesting information obtained from the FTIR spectra was the presence of sulfate. These species are indicated by the fairly broad peaks centered at 1200 and 650 cm^{-1}. Although there was only a small amount of sulfur in the fuel, the sulfate could have come from oxidized sulfur. But it was felt more likely that the sulfate came from the lubricant, probably from the sulfonate detergent or the ZDTP. Such evidence supports a minor interaction of fuel/lubricant contributing to the pintle deposit, with the overwhelming cause coming from the fuel.

INJECTOR CLEAN-UP TESTS

We began a program to determine if any of our commercial detergents would clean-up the injectors. We chose to check several additives at 500-ppm concentration using emission data to evaluate clean-up effects. Although all additives were somewhat effective at the 500-ppm level, Additive A was the most cost effective.

Typical clean-up data for Additive A are shown in Table 2 for two sets of fouled injectors. Based on changes in CO emissions, both sets of fouled injectors were cleaned up almost immediately. Drivability improved dramatically in the initial 20 miles of driving -- just prior to the emission check.

Table 2

Additive Clean-Up Tests -- Chrysler Injectors
1985 Chrysler LeBaron Turbo 2.2L Engine
Indolene and Additive A @ 500 ppm

	Bag 2-Hot 72 CVS Emissions, g/mile			
	New	Fouled Injectors		
Emission	Injectors	0 Miles	40 Miles	10 Gal
			Set No. 4	
HC	0.056	0.103	0.049	0.060
CO	0.889	2.034	1.013	0.969
NOx	0.240	0.495	0.205	0.175
		Set No. 24811		
HC	0.056	0.150	0.059	-
CO	0.889	5.673	1.571	-
NOx	0.240	0.139	0.172	-

Based on these emission test results, it appeared that the most effective additive would clean up Chrysler injectors in very short mileage at 500 ppm. Set No. 4 in Table 2 remained in the car until about 10 gallons of fuel had been used. Effective clean-up had occurred in the initial 40 miles, and additional mileage had only a minor positive effect on this set of injectors. The second set of fouled injectors (No. 24811) were tested at 500 ppm in order to verify the previous clean-up operations. Although this set had higher CO levels than the first, substantial clean-up also occurred in the first 40 miles, as seen in Table 2. Thus, two different sets of injectors were cleaned up within 20-40 miles at 500 ppm of Additive A.

Our next step in the test program was to determine if a more reasonable concentration (i.e., one normal in cost for premium unleaded fuel) would have a clean-up effect and, if so, how many tankfuls would be needed for clean-up. We selected 80 ppm (20 ptb) of Additive A for this work. Additional sets of injectors were obtained from Chrysler for this work. Results of the 80-ppm test are shown in Table 3. Set No. 592688 was a normal fouled set and cleaned up after 100 miles at the 80-ppm concentration. Both HC and CO levels were at new-injector levels after 100 miles and remained there until the 250-mile test was completed.

Table 3

Fuel Injector Clean-Up
1985 Chrysler LeBaron Turbo 2.2L Engine
Indolene and Additive A @ 80 ppm
Injector Set No. 592688

	Bag 2-Hot 72 CVS Emissions, g/mile		
Emission	0 Miles	100 Miles	250 Miles
HC	0.140	0.057	0.061
CO	6.179	0.830	0.867
NOx	0.211	0.323	0.445

A second set of injectors (Set B), which had been removed by a car dealer after a high concentration of detergent had failed to restore drivability, was also tested at 80-ppm Additive A. These results are shown in Table 4. Although drivability and emissions improved greatly in the first 100 miles, this set did not fully clean up but remained somewhat high in CO after 250 miles.

Table 4

Fuel Injector Clean-Up
1985 Chrysler LeBaron Turbo 2.2L Engine
Indolene and Additive A @ 80 ppm
Injector Set B (Detergent Resistant)

	Bag 2-Hot 72 CVS Emissions, g/mile		
Emission	0 Miles	100 Miles	250 Miles
HC	0.091	0.056	0.082
CO	6.827	3.783	3.636
NOx	0.091	0.110	0.150

We then tested Set B in another Chrysler LeBaron using both 500-ppm and 4000-ppm treat levels. The test data are shown in Table 5. The use of 500 ppm (125 ptb) resulted in additional immediate clean-up, as shown by the drop in CO from 3.6 g/mile (Table 4) to 2.4 g/mile (Table 5). Adding more detergent to the tank so that the concentration was 4000 ppm resulted in complete clean up of the injectors. Fuel-flow data for Set B are summarized in Table 5.

Table 5
Fuel Injector Clean-Up
1985 Chrysler LeBaron Turbo 2.2L Engine
Indolene and Additive A
Injector Set B (Detergent Resistant)

Emission	Bag 2-Hot 72 CVS Emissions, g/mile 0 Miles	500-ppm A 30 Miles	4000-ppm A 30 Miles
HC	0.091	0.104	0.063
CO	6.827	2.463	0.812
NOx	0.091	0.371	0.574

Injector No.	Injector Flow Rate,* g/min. Fouled Injector	After 4000-ppm Additive A
1	107	212
2	141	208
3	200	210
4	131	212

*Flow specification for a new Chrysler injector is 208 g/min. ± 3%.

We also checked the clean-up characteristics of Additive A using Ford injectors. The injector set had been removed from a Turbo Thunderbird at 49,000 miles. We evaluated these injectors in a Ford Merkur Turbo car, which uses the same engine and calibration as the Thunderbird. The results of this test are shown in Table 6. In the case of the Ford car,

Table 6

Additive Clean-Up Test -- Ford Injectors
Ford 2.3L Turbo Engine
49,000 Miles on Injectors
Indolene + 80-ppm Additive A

	Bag 2-Hot 72 CVS Emissions, g/mile		
	New	Fouled Injectors	
Emission	Injectors	0 Miles	250 Miles
HC	0.130	0.427	0.174
CO	1.68	2.49	2.05
NOx	0.16	0.43	0.50
	Drivability		
Cold Start	Good	6 Stalls	1 Stall
Driveaway	Good	Very Rough	Rough
3000 RPM	Good	Very Rough	Surge

CO changes were not as great as those observed in the Chrysler cars. Although 80-ppm Additive A did not appear to restore emissions to new injector levels, the improvement was excellent. Most dramatic was the improvement in drivability. The fouled set caused difficult starting, with 6 stalls observed during the initial drive-away attempts. These problems were greatly reduced after the 250 miles of driving using Additive A.

GASOHOL

Gasohol (10% ethanol in gasoline) is being widely marketed in the United States. Our past experience with carburetor detergency tests indicated that deposit clean-up was more difficult when gasohol was used as the fuel. We tested Additive A for clean-up performance in a blend of 90% Indolene + 10% gasoline-grade ethanol. The results of this test are shown in Table 7. Although injector clean-up is apparent after one tankful (250 miles), the injector with the worst initial flow rate (No. 4) needed to be run 500 miles before a stabilized idle was observed by the test drivers.

Table 7

Fuel Injector Clean-Up when Using Gasohol
1985 Chrysler LeBaron Turbo 2.2L Engine
Indolene + 10% Ethanol and 80-ppm Additive A

Injector No.	Injector Flow Rate, g/min. 0 Miles	250 Miles	500 Miles
1	218	216	214
2	161	168	202
3	208	208	208
4	107	146	158

INJECTOR KEEP-CLEAN TESTS

Although clean-up concentrations are of immediate interest to the car owner experiencing driving problems, an important consideration in the use of a gasoline detergent is the required keep-clean concentrations (i.e., the minimum concentration of detergent that will keep new injectors operating properly). We obtained a supply of detergent-free gasoline known to give injector fouling problems. This fuel was used in long-mileage tests of Additive A at two low keep-clean concentrations -- 20 and 40 ppm. Three 1986 Chrysler LeBaron Turbo cars equipped with 2.2L engines were used for this test. A driving cycle giving high injector soak temperatures was used. This cycle consisted of driving the cars for 15 minutes at 55 mph on the freeway followed by a 45-minute soak period.

Injector flow rates were determined on all three cars (base fuel and base fuel plus 20 and 40 ppm of Additive A) at 0 and 4,000 miles, or

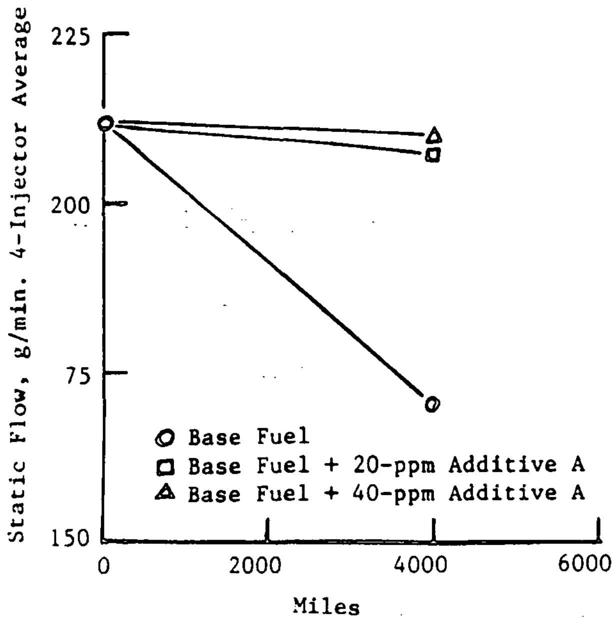

Figure 3. Effect of Mileage and Additive A on Injector Flow Rate

1986 Chrysler LeBaron Turbo Cars
2.2L Engine

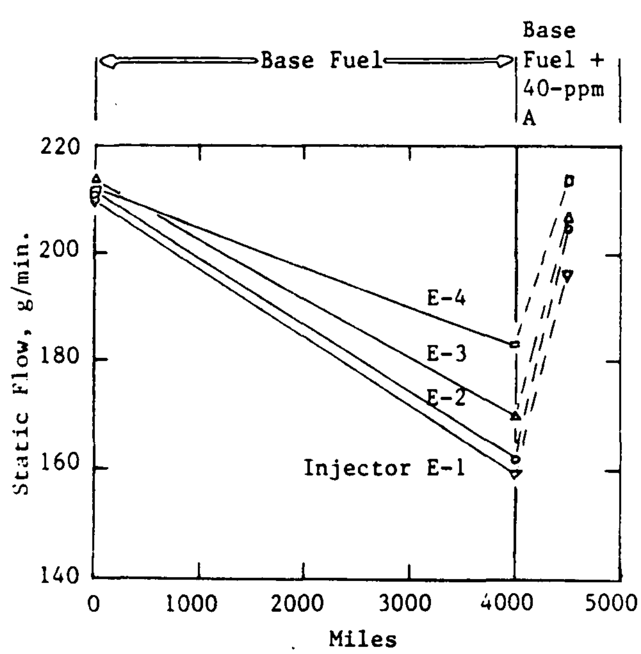

Figure 4. Effect of Mileages and Additive A on Injector Flow Rate

1986 Chrysler LeBaron Turbo Car
2.2L Engine

when serious drivability problems were encountered. Injectors were considered fouled when the static flow rate was reduced by 10-20 percent. Figure 3 shows the four-injector-average flow rates through 4,000 miles. After 2000 miles, the base-fuel car began to exhibit rough idle and poor tip-in response as the flow rate dropped. At 4,000 miles, reductions in individual injector flow rates were 24% for Cylinder 1, 24% for Cylinder 2, 20% for Cylinder 3, and 13% for Cylinder 4. Therefore, mileage accumulation on the base-fuel car was terminated at 4,000 miles.

At 4,000 miles, the base-fuel car was switched to the base fuel plus 40-ppm Additive A, and mileage was accumulated until 20 gallons of fuel had been consumed. Flow rates for the individual injectors during operation on the base fuel and the base fuel plus 40-ppm Additive A are shown in Figure 4. The injectors showed rapid clean-up on the Additive A and had nearly reached new-injector flow rates after 20 gallons had been consumed.

FUEL ECONOMY

When one or more injectors become fouled, some loss in fuel economy would be expected. Although fuel economy is difficult to measure on the road or on a chassis dynamometer, we decided to check fuel economy differences using the technique developed for the CRC five-car test. A 1986 Chrysler LeBaron was operated on a 15-minute freeway and 45 minute soak driving cycle on a fuel known to give injector fouling in about 200 cycles. The car was run an additional 6000 miles on this cycle to a drivability condition that was considered severe enough to cause unsafe driving performance. The car was then driven for one tankful of the gasoline plus 4000-ppm Additive A. Static flow checks of the injectors before and after clean-up are shown in Table 8.

Table 8

Injector Flow Rates
Static Flow Measurement

Cylinder No.	Static Flow, g/Min. Fouled Injectors	Clean Injectors*
1	214	216
2	147	212
3	90	215
4	214	218

*After one tankful of Indolene + 4000-ppm Additive A.

Triplicate fuel economy tests were run with the fouled injectors and after clean-up. The results are shown in Table 9. Weighed fuel economy was 22.13 mph for the fouled injectors and 23.51 mpg for the clean set. These data show that the car could lose about 6% in fuel economy if injectors are sufficiently fouled and that the use of a detergent package would result in maintaining new injector fuel economy levels.

Table 9

Effect of Injector Clean-Up on Fuel Economy

Test No.	Fuel Economy, mpg 1975 FTP	HFET
	Fouled Injectors	
1	19.04	27.70
2	18.93	27.75
3	19.09	27.63
Avg.	19.02	27.69
	Clean Injectors*	
1	20.47	28.79
2	20.42	28.46
3	20.56	28.83
Avg.	20.48	28.69

*After one tankful of gasoline + 4000-ppm Additive A.

CARBURETOR DETERGENCY

Carburetor detergency is still an important consideration for the bulk of gasoline powered engines throughout the world. The U.S. fleet is at least 85% carbureted, as are most transportation vehicles throughout the world. "Dirty" carburetors result in increased driver complaints and, in some cases, increased emissions if idle circuits become restricted.

We wanted to be sure that any new detergent that would keep fuel injectors clean would perform satisfactorily in carbureted engines. Therefore, a series of carburetor detergency tests were run using the CRC carburetor detergency test.(6)

The results of this study are shown in Figure 5. The tests were performed with Phillips J fuel and with Additive A at 10, 16, and 30 ppm. The results are shown in Figure 5. These results for the high deposit Phillips J fuel show deposit reductions in excess of 90% at the 30-ppm level.

Figure 5. Carburetor Detergency
Phillips J Base Fuel

CONCLUSIONS

Our studies of injector fouling have shown that:

1. Deposits that form on Bosch production fuel injectors can cause severe restriction of fuel flow.
2. These initial deposits appear to be a varnish-type material.
3. Vehicle drivability and emissions are affected when fuel flow is reduced by 10 to 20%.
4. Dirty injectors can be cleaned up and kept clean by the use of some commercial gasoline detergents.
5. Additive concentrations of 80 ppm or less can result in effective injector clean-up after one tankful.

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